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The Green Paradox

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I. Introduction

The aftermath of the Kyoto Protocol (UNFCCC, 2020a) and the succeeding Paris Agreement (UNFCCC, 2020b) has not been as fruitful in terms of carbon emission abatement as global leaders hoped for when they agreed on these international environmental agreements. In the absence of a self-enforcing mechanism, countries are economically incentivized to leave any environmental agreement (Barrett, 1994). The United States (U.S.), being the second largest emitter of greenhouse gases in the world, did so by withdrawing from the Paris Agreement in 2019 (Sælen, Hovi, Sprinz, & Underdal, 2020). Without a binding environmental agreement, global environmental policies like a carbon tax, uniform subsidies or a global emissions trading system are infeasible. Unilateral climate legislation may be implemented over a subset of countries (European Commission, 2020b), but as long as the majority of the world is not willing to share the effort, there will be no significant abatement success globally measured (see Figure 1).

Contemporary climate legislation consists of demand-side solutions such as carbon taxes, emission trading systems and subsidies on renewable energy generation – all of which have the primary purpose to make carbon consumption more expensive considering that less consumption is equivalent to less emission. However, data on carbon emission (see Figure 1) suggests that the carbon savings of some countries are simply being emitted elsewhere. Hence, demand-side environmental policies, which are not implemented on a global scale, are rendered useless if not blatantly detrimental. In addition to this Spatial Carbon Leakage (Eichner & Pethig, 2011; van Long, 2015), owners of fossil resources are watching the growing political climate awareness with great concern. Subsequently, suppliers fear that the future market for their resources will be tighter restricted and, thus, ever less profitable. In response, they bring parts of their extraction forward through increasing present production. They are thereby lowering fossil fuel prices which stimulates demand and exacerbates current pollution rates.

Hans-Werner Sinn, who was among the first scholars to analyze this issue, framed this unintended effect of environmental policies the Green Paradox (Sinn, 2008a, 2012). His major concerns are, firstly, that the supply side is not being paid enough attention to when climate-political decisions are made. Therefore, secondly, demand-side policies are flawed and have very limited efficiency (if any at all) due to the anticipative supply reaction of bringing forward extraction.

The first part of this thesis analyzes the theory of the Green Paradox (Sinn, 2008a, 2012) based on the Hotelling Rule (Hotelling, 1931) of the intertemporal distribution of exhaustible resources and elaborates which economic factors are the cause of its occurrence. Conversely, there are also several market conditions, such as endogenous fossil stocks, stock dependent extraction costs and the risk of owning stranded assets, that are countervailing the effect of a Green Paradox and potentially even its occurrence. Chapter III. is dedicated to these opposing factors and offers an analysis of their effect. The crucial distinction between a weak (short-term emissions rise) and a strong (cumulative climate damages are exacerbated) Green Paradox is made in the fourth chapter. It is further shown how the uncertain shape of the damage function (i.e. the functional relationship between timing and amount of emission and the corresponding environmental damages) has massive influence on the importance of a weak Green Paradox and, thus, on the way environmental policy measures should be designed.

In the following, based on this theoretical framework, the common environmental policies are analyzed in light of the Green Paradox theory. Considerations on whether these demand-side policies indeed trigger a weak and strong Green Paradox are further developed. This part of the thesis also includes a detailed look into the ideal first-best solution for the climate issue as well as an explanation why this first-best carbon tax is infeasible and second-best solutions must do the job. Sinn´s (1984) own proposal – a source tax on the capital income of fossil fuel owners that amends the Hotelling Rule in a way that fossil suppliers prefer postponing extraction rather than bringing it forward – is evaluated in chapter VI.. Therefore, its effectiveness in mitigating climate change is compared to the aforementioned demand-side measures.

A finalizing summary of the empirical literature on the Green Paradox discloses a sparse empirical foundation for the broad theoretical debate. It is argued that uncertainty about the existence of a (weak) Green Paradox and its correlation with environmental damages in the long run prevents governments from credibly implementing sound political measures.

In the conclusion, all these variables affecting the Green Paradox are summarized and it is examined how they are supporting or contradicting Sinn´s (2008a, 2012) assessment of environmental demand-side policy measures.

II. Argumentation and Theoretical Reasoning behind the Green Paradox

In order to be able to critically assess the Green Paradox theory (Sinn, 2008a, 2012) in the following chapters, this first chapter is dedicated to analyzing its reasoning and argumentation. Hence, there is little criticism involved in the succeeding sub-chapters since they mainly reflect Sinn´s (2008a, 2012) hypothesis. It is therefore strongly recommended to not take this chapter out of context and always set it in relation to the corresponding criticisms of chapters III-V.

II.1. The Neglected Supply Side

The United Nations have set ambitious goals to curb carbon dioxide (CO_2) emissions and some countries, in particular the ones within the European Union (EU), already demonstrated significant abatement success. The European countries decreased their cumulative annual CO_2 emission by 25% over the last 30 years. Yet, global pollution increased by almost 60% over the same period of time (see Figure 1).

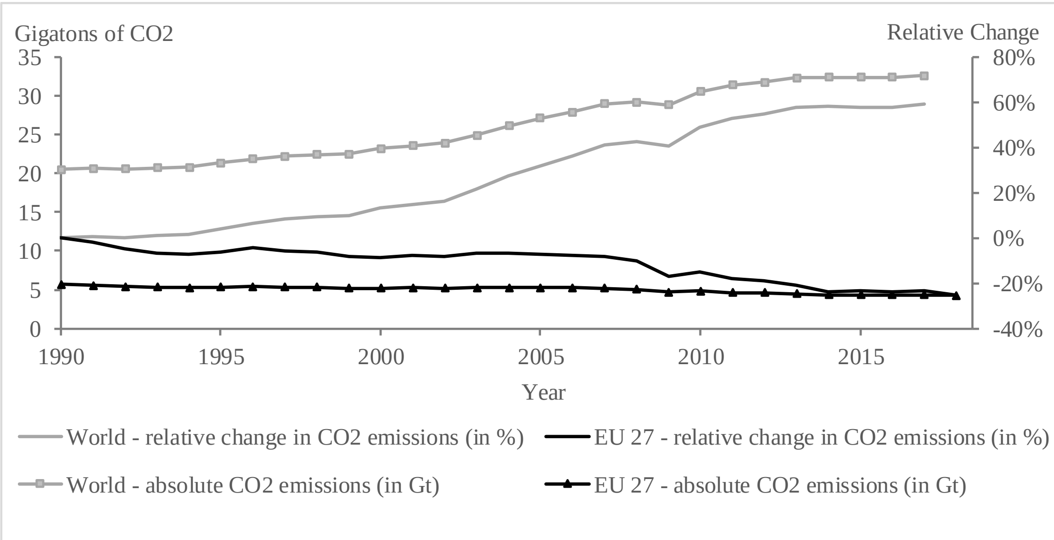

Figure 1: Carbon Dioxide Emissions and Abatement on Global and European Scale (1990-2018)

Source: Own figure based on data retrieved from EEA (2020) & OECD (2020a)

Apparently, the effort and economic burdens the EU (besides some other countries) is willing to devote are not sufficient to fight climate change on a global scale and may even appear useless when considering the aforementioned data. Yet, this dreadful consequence of international climate engagement is not determined to remain. Besides green technology advancements and leading-by-example spillover effects, environmental pioneering can also foster well-implemented policies. So far, the environmental policies implemented in compliance with the Kyoto Protocol (UNFCCC, 2020a) and the succeeding Paris Agreement (UNFCCC, 2020b) have the principal objective to lift the price of carbon-intensive energy sources in order to contract demand and lower emissions. Regarding the global market, this reasoning is valid: Less aggregated demand for fossil fuels results in less quantities consumed. However, environmental policies like carbon taxes and subsidies on renewable energy sources are not implemented on a global scale which distorts the demand side of fossil markets. Assuming the supply side to be constant, the reduced demand of committed countries results in lower global fossil prices as supply outweighs demand. Hence, uncommitted countries are incentivized to extend fossil consumption fueling unilateral economic development and, thus, to emit the greenhouse gases elsewhere. This so-called Spatial Carbon Leakage renders demand reductions of a subset of countries useless, unless the reduction is uniform across the majority of demanders (Eichner & Pethig, 2011; van der Ploeg, 2016; van Long, 2015). Due to the stressed trade-political situation across the globe and the rapid economic emergence of countries like China, India and several African ones, the success of global CO_2 abatement based on uniform fossil demand reductions is jeopardized (van der Ploeg & Withagen, 2014).

The European Green Deal strives to make Europe climate-neutral in terms of greenhouse gas emissions until 2050 (European Commission, 2020b). Yet, it shows perfectly how countries, which are committed to curbing their carbon footprint, base their effort on reducing fossil fuel demand. Under the EU Emissions Trading System (ETS) (European Commission, 2020a), the annual CO_2 emissions are capped and successively decreased via tradable permissions. In addition, supplementary policies set targets on alternative energy sources and efficiency enhancing technologies. This makes the EU Green Deal indeed a comprehensive approach to decarbonize and decouple economic growth from fossil resource use by transforming the economy in a circular one (Smol, Marcinek, Duda, & Szołdrowska, 2020). Nonetheless, this does not necessarily imply that global greenhouse gas emissions are altered at all. Unless the aggregated world demand for fossils contracts (which is, as mentioned, questionable), declining supply quantities are the only way to effectively decrease global consumption of fossil resources (Sinn, 2008a, 2012).

As Sinn (2008a, 2012) emphasizes, demand-side policies do not only suffer from Spatial Carbon Leakage and, hence, limited effectiveness. Announced climate protection measures threaten the future commodity markets of fossil resource owners. Therefore, suppliers preempt less lucrative trading opportunities in the long run by bringing extraction forward and selling more of their resources short-term. This unintended Green Paradox arises from demand-tackling policies which do not account for the resource owner´s behavior. Neglecting the supply side and, thus, implementing flawed climate policies can turn the desired effect upside down and exacerbate pollution (European Research Council, 2016; Sinn, 2015).

According to Sinn (2008a, 2012), the inability of environmental politics to include the supply side into their considerations results in two hazardous effects. Firstly, resource owners react in an unanticipated manner hindering demand-side policies from being effective and, secondly, the option of supply-side solutions is ignored. This political unawareness came as no surprise as, until the late 2000s, the scientific community analyzing the economics of environmental policies was silent about the supply side, too (Sinn, 2008b, 2015). There has been plenty of research on the economics of climate change over the last decades – most noteworthy is probably the Stern Review which covers a vast scope of climate-related economic topics (Stern, 2007). However, the importance of the supply side was mainly introduced into the scientific and public debate by Sinn (2008a, 2012) and his theory about the Green Paradox.

II.2. Intertemporal Allocation of Resource Extraction

Unlike the producers of normal, reproducible goods, who optimize their supply quantities based on static-equilibrium calculations of production costs and revenue, the optimization problem of fossil fuel owners is dynamic (Hotelling, 1931). As their stock S is exhaustible, the decision is not how much but when to extract (R_t denotes the extracted quantity for a given time period t). This means each unit that is extracted and sold today cannot be sold tomorrow ($R = -dS/dt$). Hence, the opportunity cost of future exploitation needs to be incorporated into present supply considerations. The optimization problem breaks down into the following intertemporal trade-off: Each unit can either be extracted and sold today and the according profit P_1 is invested on the capital market at the present market interest rate i or the unit is left in situ for later exploitation. Leaving the stock under surface yields the benefit that, due to growing scarcity, the value of the commodity rises over time ($P_2 > P_1$). Intertemporal optimality ($R_1 = R_2$) requires the two off-trading income streams to be equalized. That is, the appreciation of the stock in situ is aligned with the interest generated by investing the sold resource´s revenue on the capital market ($P_2 = (1+i)\ P_1$). This optimality condition of intertemporal resource allocation is called Hotelling Rule (Hotelling, 1931). In short, the Hotelling Rule states that the price of fossil resources (driven by scarcity rents) has to grow at the same rate as the market rate of interest.

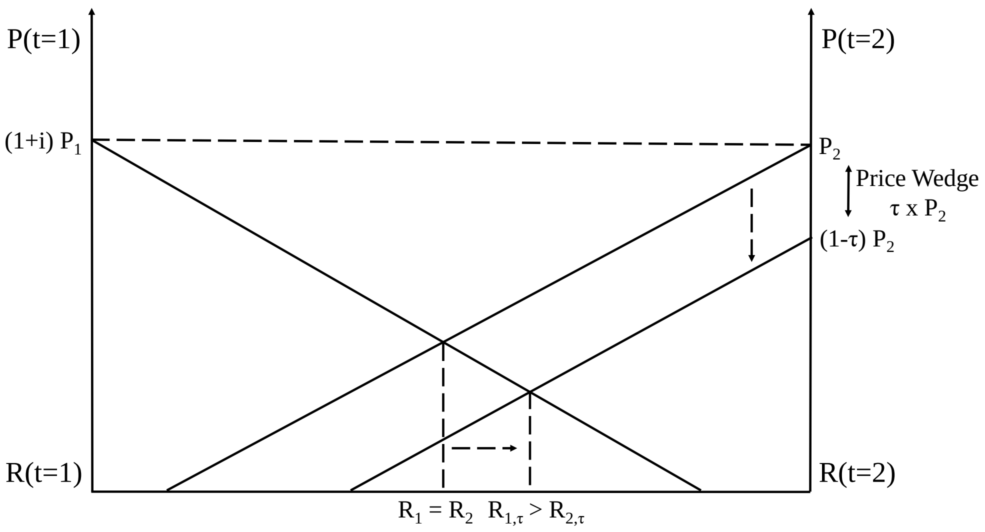

Figure 2: Price Wedge under Hotelling Rule

Source: Own figure based on Hotelling (1931)

Figure 2 illustrates the Hotelling Rule, where the x-axis represents the exogenous stock S and the extraction rates of each period. In the first case without a carbon tax, the inverse demand functions intersect such that the equilibrium condition $R_1 = R_2$ is satisfied. If a carbon tax τ is implemented, the profit of the seller decreases. Either the resource price rises with the tax and, thus, demand decreases, or the net price falls for the gross price to remain constant. Either way, the marginal revenue per unit sold decreases under a carbon tax (Sinn, 2008a, 2012).

In the latter case, suppliers decrease net prices sufficiently to countervail the tax, leaving the demanded quantity unchanged. This stands in strong contrast to the main objective of common environmental politics, namely to contract demand. The supply reaction to a price change in a given period is determined by its price elasticity, which will be explained in more detail in chapter II.3. The intertemporal extraction decision, however, is mainly influenced by the price wedge (i.e. the difference between the supply price in the tax scenario and the one that would have prevailed without a tax). A carbon tax implemented as of immediately would uniformly distort the extraction decisions in both time periods.[1] Yet, the issue with announced political decisions is that they take several years to be discussed and passed through until they are implemented. Furthermore, most carbon taxes and quantity constraints become more restrictive over time which basically makes them announced future policies, too (Smulders, Tsur, & Zemel, 2012). During this implementation lag, producers are incentivized to amplify extraction before the tax or constraint limits their commodity´s value or salability. Additionally, cleaner fossil fuel sources (e.g. gas) may be saved for the constrained era and dirtier fuels (e.g. coal) are exploited short-term. As a result, the extraction rate and emissions are increased during implementation lags (Di Maria, Smulders, & van der Werf, 2012). This is because announced environmental policies do not distort present prices but future ones (distortion effect). Accordingly, the Green Paradox states that current extraction decisions react to future price changes (Long & Sinn, 1985; Sinn, 2008a, 2012). In Figure 2, the second intersection of the inverse demand functions, with the second period being depreciated by a carbon tax τ, shows how suppliers anticipate the time-dependent tax burden and increase their present extraction rate $R_{1,\tau}$ because they devalue future extraction $R_{2,\tau}$. Contrariwise, a tax rate which is high today and falls over time would induce fossil fuel owners to postpone exploitation since it is more lucrative in later periods (Sinclair, 1992) (see also chapter V.2).

Thus, according to the Hotelling Rule, the price wedge does not distort the extraction path if its discounted value is constant over time. In other words, the product of tax rate and net value share of extraction (price adjusted by extraction costs g(S)[2]) has to rise with the rate of interest in order for the extraction path to be in equilibrium (Sinn, 2008b).

$$\hat{\tau} \ \frac{P(R,t)}{g(S)} = i \tag{1}$$

[1] The infinite continuous time horizon is reduced to two discrete periods (“today” and “tomorrow”) to visualize the considerations more comprehensibly.

[2] In the Hotelling Rule exploitation is assumed to be costless and, hence, extraction costs are neglected in Figure 2. Formulas 1 & 2 represent a more general case, where extraction costs are positive and stock-dependent such that dg/dS < 0.

The tax growth rate $\hat{\tau}$ required for intertemporal extraction indifference therefore depends on the product of discount rate and the share of extraction costs in revenue (Sinn, 2008b).

$$\hat{\tau} = i \; \frac{g(S)}{P(R,t)} \tag{2}$$

II.3. The Impact of Price Elasticities

As indicated before, the Green Paradox is all about reactions to price changes. Therefore, it is crucial to understand how the different agents´ price elasticities behave. For the demand side, it is apparent that with rising fuel prices the demanded quantity drops. The concavely decreasing demand curve (Figure 3) also incorporates the residual demand that will probably never disappear due to incomplete substitutability of fossil fuels (see chapter II.4.).

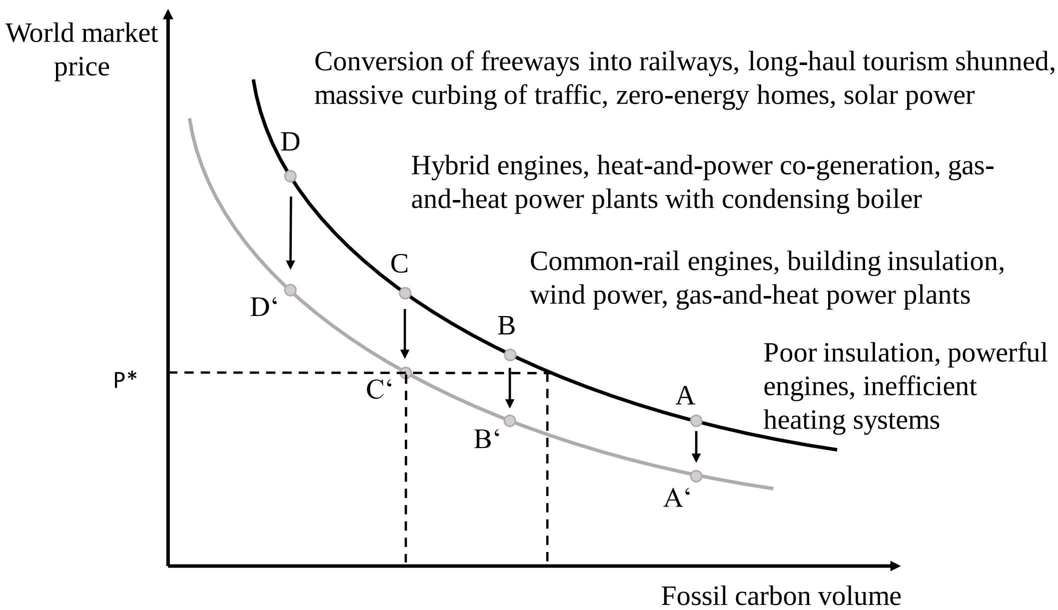

Figure 3: Carbon Demand Shift under Environmental Policies

Source: Own figure based on Sinn (2012)

The letter-denoted points on the curve show how demand reacts to price changes by introducing new technologies which are either energy-efficient in the high price scenario or energy-intensive if fossil fuel became relatively cheaper. The upper curve represents a pure market scenario without any government interventions. The lower one corresponds to a scenario with green policies where substitutes are competitive at a lower price level already. Apparently, the government interference decreases the demanded fossil fuel quantity for any given price level P* (Sinn, 2008a, 2012). The slope of the demand curve is given by the price elasticity of demand. Although a higher price elasticity of demand exacerbates the Green Paradox by reacting stronger to the short-term price drop on the global fossil fuel market (van der Ploeg, 2016), for this consideration the given demand elasticity in Figure 3 stays put to keep the focus on the supply side.

Figure 4 illustrates how different levels of supply elasticity affect the outcome of environmental policies. In case of a perfectly elastic supply, the demand reduction induced by environmental policies fully translates into the desired quantity reduction. If supply is perfectly inelastic however, the shift is a pure price reduction leaving the quantity unchanged. In this scenario, the environmental policies solely alter the world market price of fossil fuels which results in the aforementioned Spatial Carbon Leakage (Sinn, 2008a, 2012).[3]

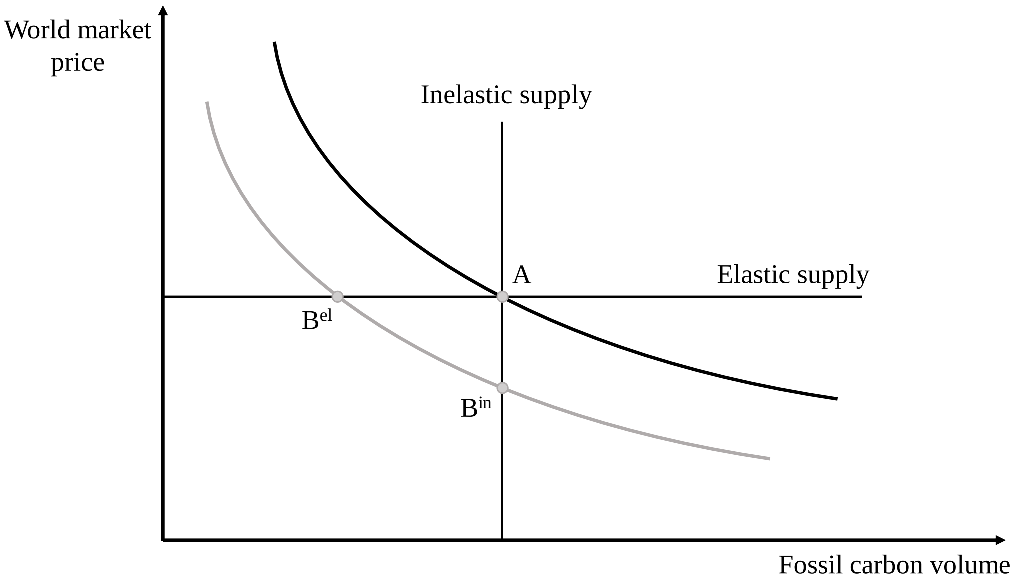

Figure 4: The Impact of Supply Price Elasticity

Source: Own figure based on Sinn (2012)

By anticipating future green policies, an inelastic supplier of fossil fuels foresees lower commodity prices and, hence, brings extraction forward. A perfectly

[3] The crucial importance of the suppliers´ price elasticity was evident in April 2020 when the world´s leading oil producers (United States, Saudi Arabia and Russia) did not react to the demand plunge triggered by the Covid-19 crisis. By strictly sticking to their output quantities, they overwhelmed market and storage capacities leading to a negative U.S. crude oil price for the first time in history (Ambrose, 2020).

elastic supplier, on the other hand, faces constant prices over time and is indifferent between extracting today or tomorrow.

In conclusion, the more inelastic supply and the more elastic demand are, the less effective price increasing environmental demand-side policies become.

II.4. Substitutability of Fossil Fuels

Environmental policies are not only about curbing fossil fuel consumption but further include fostering carbon-neutral energy sources. Eventually, the goal is to substitute fossil fuels with renewable energy sources and, hence, to decouple energy demand from greenhouse gas emissions. The reasoning behind subsidizing renewable energy sources is similar to the one behind carbon taxation. While a carbon tax internalizes the negative externality of global pollution, a green subsidy internalizes the positive externality of learning-by-doing. Learning-by-doing refers to endogenous technological growth and implies that the costs of technology will decrease along rising experience (Arrow, 1962). Since the market itself does not reimburse for the entire positive externality of research and development activities, a subsidy is required to avoid a suboptimal learning rate (Edenhofer, Bauer, & Kriegler, 2005).

But the mere presence of so-called backstop technologies makes fossil fuel suppliers worry about their future markets and shortens their planning horizons. In this context, a subsidy on renewables is equivalent to a tax on carbon-intensive energy sources: If the characteristics of the supply-side are not taken into account, unanticipated effects may arise due to the intertemporal distortion effect and current extraction is increased (Hoel, 2011; Levy, 2000). Given that fossils and renewables are perfect substitutes, fossil owners also tend to over-extract and flood the market with cheap fossil fuels in order to depress the world energy price and counter subsidies. Because renewable energy sources still do not have a significantly lower breakthrough point than fossil fuels, limit-pricing is an effective measure to keep them out of the market – albeit, the costs of renewables are decreasing at an accelerating pace (IRENA, 2020). This constellation with fossil fuel owners as monopolistic supplier and renewable energy sources as competitive fringe has been widely analyzed in the literature (e.g. Chakravorty & Liski, 2013; Fischer & Salant, 2012; van der Meijden & Withagen, 2019).

In terms of their physical characteristics, some part of fossil and renewable energy sources are indeed perfect substitutes – primarily for the part of energy demand that is already covered with electricity (~24% in 2016 (IRENA, 2019)).[4] Yet, there are still diverse applications of fossil fuels which cannot be substituted by electricity. Foremost, the issues of storage and transportation are major drawbacks regarding the applicability of electricity to several energy requirements (Leonard, Michaelides, & Michaelides, 2020). Biofuels have the chemical characteristics to solve these issues but are strongly constrained by (forest) space and ethical questions of food shortage (Hassler & Sinn, 2016; OECD & FAO, 2019). Hydrogen fulfills all necessary properties in terms of storability and energy density in order to replace fossil fuels and is considered by many as the key asset towards a clean energy society. Yet, the hydrogen industry lacks the capabilities to provide the required volumes for a large-scale incorporation of hydrogen fuel cells (Thomas, Edwards, Dobson, & Owen, 2020). These among others are reasons why it is not foreseeable that global demand for fossil fuels will fully cease in the mentioned sectors within the close future. Furthermore, some residual demand in specific sectors will potentially never disappear (see Figure 3) (Luderer et al., 2018; Sinn, 2008a, 2012).

For the share of fossil fuels that is indeed replaceable, the assumption of perfect substitutes is valid. But for the market as a whole, renewable and fossil energy sources remain heterogenous and must be considered as imperfect substitutes. Correspondingly, the Green Paradox is triggered by subsidies because fossil fuel owners fear for their market share in those sectors where renewables are indeed substitutes for their commodity.

II.5. Legal and Economic Expropriation Risk

The OPEC (Organization of Petroleum Exporting Countries) cartel owns a self-announced share of almost 80% of the global crude oil reserves (OPEC, 2019). The members, some of whom under unstable political conditions (e.g. Venezuela), base vast amounts of their fiscal expenditures as well as their leaders´ personal enrichment on the revenue generated by oil exports (Alkhateeb, Mahmood, Sultan, & Ahmad, 2017; Halff, Monaldi, Palacios, & Santos, 2017; Ikein, 2017). Regarding

[4] As the environmental awareness is constantly growing among energy demanders, price is not the only determinant of a favorable commodity. The ecological aspect gains importance and, hence, customers are willing to pay higher fees for “green electricity” generated from renewable sources (Knapp, O'Shaughnessy, Heeter, Mills, & DeCicco, 2020). Accordingly, electricity is not perfectly homogenous and fossil sources and renewables are no perfect substitutes in the form of electricity either. The discussion about the consequences of green preferences within the electricity market for the substitutability of fossil and renewable energy sources is left for further research.

the basic model of exhaustible resources, the optimization behavior of resource owners depends strongly on their planning horizon which is generally considered to be infinite under given tenure security (Hotelling, 1931). Notwithstanding, ill-defined and weakly enforced property rights for private extractors as well as the fear of political upheavals in the case of state-owned fields shorten their planning horizons (Chichilnisky, 2005).

In economic terms, the extraction path is distorted in a way that fossil fuel owners under limited tenure security do not only discount by the interest rate but further include the risk of expropriation into their discount rate (Sinn, 2008b). In the absence of a carbon tax, where π denotes the instantaneous expropriation probability for each point in time, the Hotelling Rule states that the extraction decision is in equilibrium if

$$i + \pi = \frac{P(R,t)}{g(S)} \tag{3}$$

(Sinn, 2008b). The scarcity-driven price has to rise faster once the expropriation probability is included in the intertemporal optimization. This implies that the fossil stock decreases at a higher pace and, thus, short-term extraction increases. As is shown in chapter II.2, a carbon tax must rise with the product of discount rate and the share of extraction costs in revenue in order to be neutral over time. In case of a given expropriation risk π, this corresponds to

$$\hat{\tau} = (i + \pi)\,\frac{g(S)}{P(R,t)} \tag{4}$$

(Sinn, 2008b). Since the risk of overextraction is increased by insecure property rights, these circumstances have to be taken into account when designing a carbon tax and its growth path in order to avoid further deterioration (Sinn, 2008b).

The political discussion of this issue is well beyond the scope of this thesis and will not be further discussed. Nonetheless, the understanding of how the risk of expropriation enhances short-term extraction is pivotal in order to assess the implications of the Green Paradox. The implementation of environmental policies constrains the salable quantities of carbon-intensive commodities either directly or via price-inducement. Therefore, they can be interpreted as economic expropriation since their aim is to lock parts of the reserves in situ forever (Sinn, 2008a, 2012). Equivalently to the case of legal expropriation risk, suppliers react to the anticipated economic expropriation by shortening their planning horizon and bringing forward extraction.

III. Opposing Factors to the Green Paradox

In chapter II, the economic reasoning behind the theory of the Green Paradox is analyzed. In this chapter it is shown that, besides well-designed political interventions, there are also economic factors that oppose the occurrence of a Green Paradox or mitigate its impact respectively. In particular, these factors are endogenously determined rather than exogenously given fossil stocks, scarcity-driven extraction costs that are rising indefinitely towards depletion and the risk of owning stranded assets once fossil supply begins to cease. Each factor will be analyzed separately in the following sub-chapters.

III.1. Endogenous Fossil Stocks

The Hotelling Rule is based on strong assumptions. One of them is the assumption of a non-increasing exogenously given stock of fossil resources that needs to be allocated over time through dynamic optimization of per-period extraction rates (Hotelling, 1931). Through exploration activities and technological advancements, however, new resources are constantly discovered and already discovered ones become economically exploitable reserves. Sinn (2008a, 2012) argues that the great majority of resources has already been discovered and, thus, exploration can be ignored and stocks taken as exogenously given. For conventional fossil fuels this may be true. The rising production of shale oil and gas as well as the according research focus on drilling and fracturing technologies, especially in the United States and developing nations, suggest, however, that exploration and research still have significant impact on fossil markets (Arezki, van der Ploeg, & Toscani, 2016; Kim & Lee, 2018; Luderer et al., 2018).

Therefore, the overall amount of fossil fuels, both already extracted or still exploitable, is increasing over time. This may sound like catastrophic circumstances for the fight against climate change, since the carbon-intensive energy sources are rising in quantity and, hence, are even more challenging to be withheld from usage. But regarding the discussion about climate policies, the reality of endogenous fossil stocks rises a whole new argument in favor of interventions. As exploration and research activities are very costly and highly risky, they are only reasonable if large revenues can be expected from new reserves. McGlade & Ekins (2015) therefore argue that exploration expenditures are in fact a waste of money because the Paris Agreement (UNFCCC, 2020b) sets such restrictive boundaries to the emitable carbon volumes that the already existing reserves are not even fully extractable. By limiting the future profitability of fossil resources, climate legislation discourages exploration and, thus, reduces the carbon quantity available for exploitation compared to business as usual (Österle, 2016).

As the cumulative stock shrinks, the extraction rate in every time period is reduced proportionally to the pre-legislation optimum. This impact of an intervention (e.g. carbon tax) opposes the distortion effect which emphasizes that current extraction is increased. Thereby, once endogenous fossil stocks are considered, the occurrence of the Green Paradox is mitigated (Cairns, 2014).

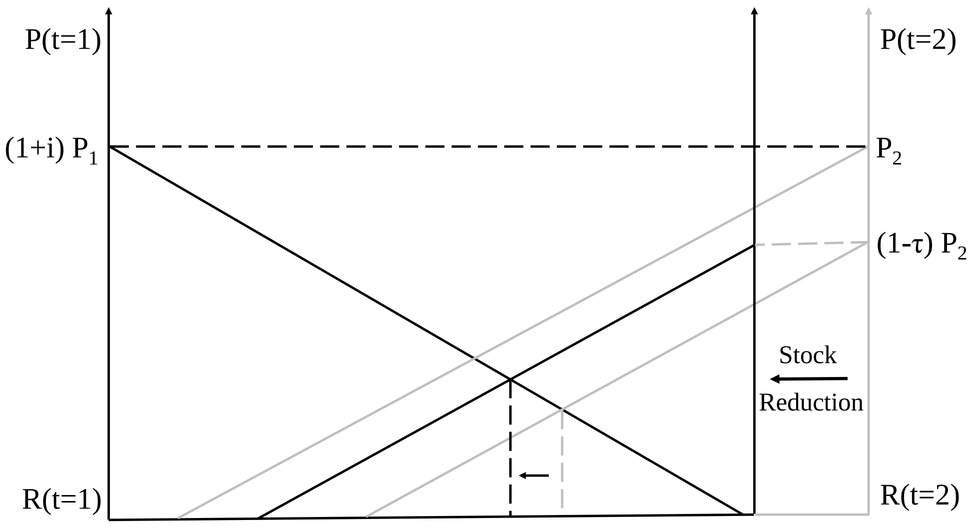

Figure 5: Endogenous Fossil Stock Reduction under Carbon Taxation

Source: Own figure

Figure 5 incorporates the contraction of the fossil stock due to the reduction of investments in exploration and research activity (divestment effect). Because the tax implementation reduces current explorations, future stock quantities will shrink. This effect accounts for the left-shift of the right y-axis representing the second time period. The newly arranged intertemporal equilibrium signals both, a reduction of period-one and period-two extraction rates.[5]

Compared to business as usual, the effect of climate legislation on contemporary extraction is ambiguous. While the distortion effect induces an increase in R_1 on costs of a reduction in R_2 (see Figure 2), the divestment effect makes both extraction rates contract. The cut in R_2 is definite, but the behavior of R_1 depends on how the tax is designed. A small growth rate leads to less temporal redistribution (weak distortion effect). A high growth rate, on the other hand, limits total emissions more significantly but leads to faster extraction (strong distortion effect) (Österle, 2016). Nonetheless, under a short implementation lag and, thus, less temporal redistribution, the divestment effect may be able to prevail over the distortion effect (Bauer, McGlade, Hilaire, & Ekins, 2018). This implies that no Green Paradox would occur all the while cumulative extraction is effectively decreased.

III.2. Stock-dependent Extraction Costs

Another strong assumption the Hotelling Rule is based on, is the one of costless extraction. By the time Hotelling (1931) framed his theory, neither significant economical nor environmental costs of fossil fuels were foreseeable. Therefore, the sole cost of extraction in his model is the opportunity cost of consumption which is given by the price appreciation through scarcity (Hotelling, 1931). As Sinn (2008a, 2012) mentions in his Green Paradox theory, besides the oppressive societal costs of pollution there actually are economic extraction costs of fossil reserves. These production costs are defined to a large extent by the accessibility of the commodity. Since the easier-to-access fields will be exhausted first, fossil suppliers will have to tap more expensive fields successively as the overall stock of fossils declines. For conventional fossil energy sources, they are very low though.[6] Too low to assume that the costs of production alone, albeit rising, will effectively limit their profitability to such a degree that supply ceases.

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[5] Note that the equilibrium is shifted to the left indicating that R_2 rather increases, but due to the left-shift of the right y-axis the area between equilibrium and y-axis does indeed narrow.

[6] According to long-term estimates (until 2030) of the ifo Institute, the cost-to-price ratio of conventional fossil energy sources will lie between 23% for crude oil and 56% for coal (Karl, 2010). This supports the assumption that, unlike the case of normal goods, the price of conventional fossil resources is not primarily determined by production costs. Hence, they are unlikely to become prohibitively high anytime soon.

Unconventional energy sources like shale oil, however, are under much higher price pressure. Due to increasing stock-dependent extraction costs and international trade-political reasons, shale oil producers are already at the edge of profitability (Guira, 2020). Thus, in the case of shale oil, the stock-dependent extraction costs are sufficient to limit exploitable volumes significantly. Conventional fossil fuels, despite having huge profit margins, are also theoretically limited by rising production costs. With a subsidized carbon-free backstop technology setting a lower price ceiling, their production quantities are therefore also constrainable (van der Ploeg & Withagen, 2015). In any case, the producer´s revenue is decreased if increasing extraction costs are taken into account.

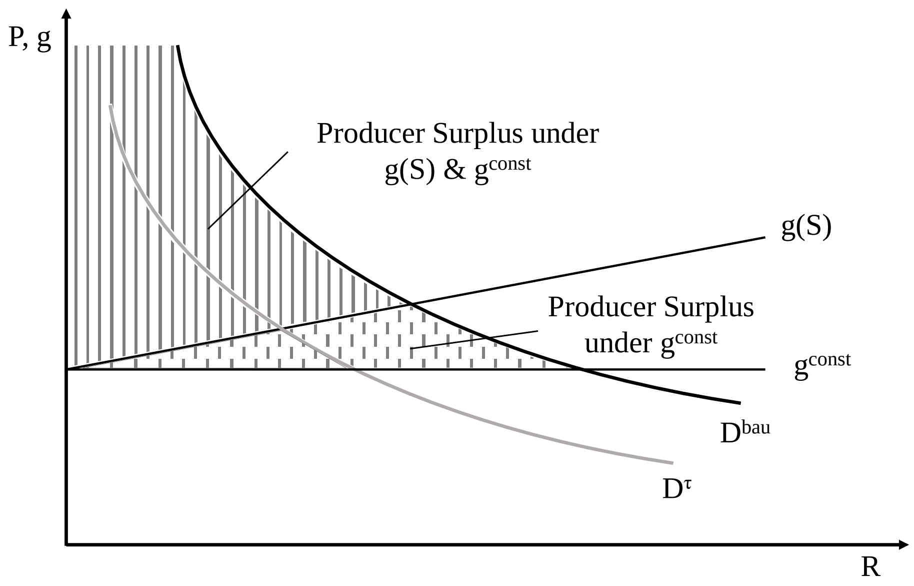

Figure 6: Producer Surplus under Stock-Dependent Extraction Costs
Source: Own figure

Figure 6 shows a comparison of the producer surplus given either constant (g^{const}) or increasing stock-dependent extraction costs (g(S)). For any positive extraction quantity and price level, the producer surplus (i.e. the area between demand curve and cost function) is smaller under the stock-dependent cost function. As expected, the introduction of a carbon tax reduces demand (D^{τ}) and further reduces the producer surplus compared to business as usual (D^{bau}). The intersection of demand curve and cost function indicates the point of cumulative extraction where an additional unit is not economically exploitable anymore. Apparently, the cumulative extraction quantity is also constrained by both the assumption of increasing costs and a carbon tax. A carbon-free backstop technology would add a constant price ceiling to the model which, in order to be effective, had to be below the equilibrium price of the intersection between cost function and demand curve.

Rising, stock-dependent extraction costs limit the producer surplus and cumulative extraction. Similar to the aforementioned divestment effect, extraction rates are reduced in all periods of time countervailing the distortion effect. In the case of cheap conventional fossil fuels, however, increasing production costs are not enough to effectively keep their supply within climate thresholds and a competitive carbon-free backstop technology is required. By subsidizing this clean technology, the distortion effect is strengthened and short-term emission will be aggravated. Yet, the long-term cumulative emission will shrink in line with total extraction (Gerlagh, 2011).

The Heal model (Heal, 1976) incorporates stock-dependent extraction costs and a price cap set by a backstop technology. Therefore, the model concludes total extraction to be endogenously determined. It is widely used in the literature to contradict the Hotelling model and the Green Paradox theory (e.g. Gerlagh, 2011; Hoel, 2012; van der Ploeg & Withagen, 2012; van der Werf, 2012).

III.3. The Risk of Stranded Assets

The 2°C limit global leaders have agreed on with the Paris Agreement (UNFCCC, 2020b) severely restricts the total amount of emitable CO_2. Further exploration investments are therefore disincentivized. Hence, the endogenously determined fossil stock can be expected to grow less than it would have in the business as usual scenario. Existing fossil reserves are as well under risk of remaining unexploitable: McGlade & Ekins (2015) predict that one third of all oil reserves and half of the gas reserves will never be exploited if the 2°C threshold is maintained.

These stranded assets are connected to sunk costs in a way that they are neither recoverable nor transferable, but they describe a narrower phenomenon. Mostly being referred to in the context of climate change mitigation, stranded assets are lost investments due to the departure from carbon-intensive value chains (Harnett, 2018). This implies that stranded assets do not only define the property of fossil fuel suppliers but include all industries involved in the value creation through fossil fuel combustion. Assets of power utilities, that are solely dedicated to the conversion of fossil fuels, can be expected to become liabilities (Baldwin, Cai, & Kuralbayeva, 2020). Stock market investors are progressively considering low-carbon investments appealing and start to refrain from those who are not signaling willingness to withdraw their business from carbon assets (Monasterolo & Angelis, 2020; Saltzman, 2013). The risk of stranded assets affects demand[7] and supply, pushing both to reduce their investments in fossils, and the demand side is further incentivized to look out for carbon-neutral alternatives. The corresponding impact on the fossil fuel market (fossil stock reduction and demand shift) and implicit emission reductions can be inferred from Figures 5 & 6.

So far, the risk of stranded assets is explained to yield positive reactions in terms of premature carbon abatement. Yet, entire industries are at stake if expectations and corresponding long-term investments are not adjusted to that risk. Transparent policies are required and reliable commitment to announced policies must be plausible for companies in order to be able to reevaluate long-term investments efficiently (Sen & Schickfus, 2020). For emerging regions which heavily rely on fossil exports (e.g. the Middle East, China, Latin America), the risk of stranded assets puts their economic development in jeopardy and a reassessment towards green transformation is urgently needed from the political side (Ansari & Holz, 2020; Shearer, Myllyvirta, Yu, Aitken, & Mathew-Shah, 2020). In general, resolving uncertainty about environmental policies is key to make stranded assets an opportunity rather than a threat (van der Ploeg & Rezai, 2020).

The demand side anticipates the long-term scenario where demand ideally will be independent from fossil fuels and prior investments in carbon-related assets will be stranded. Therefore, it shifts current investments and intermediate demand proactively towards carbon-free sources. Through the eyes of fossil suppliers, anticipative demanders are another threat for fossil markets which strengthens the distortion effect. The result is reduced cumulative emission, but short-term exploitation and pollution are exacerbated (van der Ploeg, 2020).

IV. The Cumulative Effect of Environmental Policies over Time

Most of the economic factors and environmental policies mentioned in the previous chapters stand in an ambiguous relation to the Green Paradox. While they potentially lead to an increased short-term extraction, cumulative carbon quantities and pollution are decreased. In the following chapter, it is explained how these two

[7] Power utilities are the biggest customers of fossil fuel suppliers and can be seen as representatives for the numerous smaller final customers. Stock investors represent corporate demand and their adaptability to change in this example.

effects affect each other and to which extent environmental policies are able to curb emissions short-term and in the long run.

IV.1. The Decisive Distinction between a Weak and a Strong Green Paradox

Induced by an announced carbon tax or quantity constraint, the distortion effect makes fossil fuel suppliers reevaluate their extraction distribution decision. This leads to preferred immediate exploitation because future sales are considered less lucrative (see Figure 2). The introduction of substitutes acting as backstop technology and expropriation risk as additional discount factor have the same effect on the intertemporal distribution: Today´s extraction rates are increased because fossil fuel suppliers fear that the future salability of their commodities will be strongly constrained. Sinn´s (2008a, 2012) theory emphasizes concerns that the increased short-term extraction is highly precarious and countervails the costly efforts of climate change mitigation.[8]

Gerlagh (2011) was among the first researchers to analyze the theory of the Green Paradox and critically assesses Sinn´s (2008a, 2012) hypothesis. He supports the view that short-term extractions are indeed rising due to public interventions but points out that long-run cumulative emission levels will most certainly decrease. To be more precise, he distinguishes between a weak and a strong Green Paradox. A weak Green Paradox refers to the case that current emissions are expanded. A strong Green Paradox arises when cumulative climate damages, measured at their net present value, are exacerbated. Therefore, the weak Green Paradox describes an immediate effect while the strong Green Paradox refers to an aggregate welfare effect (Gerlagh, 2011).

To assess the welfare effect of CO_2 pollution, the social cost of carbon (SCC) (i.e. the public economic cost caused by an additional ton of CO_2 (equivalents) reaching the atmosphere) is a pivotal element for understanding and implementing environmental policies. Carbon taxes are often set equal to estimates of the SCC in order to internalize the negative societal impact of private carbon combustion (this

[8] Sinn (2008a, 2012) argues that by slowing down extraction and, thus, reducing current emissions, future generations are less affected by environmental damages and suffer from a smaller economic burden. Since a smaller part of future GDP (Gross Domestic Product) has to be devoted to repairing environmental damages, the future generations are better off.
He further argues that the social rate of return from deferring extraction exceeds the market rate of interest by the climate damage that would be caused by extracting and combusting an additional value unit. Thereby, a pareto optimum can be reached by bequeathing more fossil resources to future generations at the expense of monetary investments on the capital market (Sinn, 2008a, 2012).

taxation concept is called Pigouvian tax). The SCC has the primary purpose to link climate change considerations with monetary-based economic calculations and is estimated with the help of integrated assessment models (Nordhaus, 2014). These Integrated Assessment Models (IAM) are the basis for most climate-economic discussions and decisions.[9] Under varying assumptions and data input, IAMs aim to predict climate change scenarios and the efficiency of mitigation strategies. By contrasting the costs of mitigation strategies with the corresponding SCC of inaction, the feasibility of these strategies can be assessed.

IAMs are operated under a variety of different social and economic assumptions and their output correlates strongly with them (Hare, Brecha, & Schaeffer, 2018). One type of these assumptions is the shape of the damage function which is the functional relationship between climate damages and the timing and amount of emissions. The significance of short-term emissions for overall damages, and, thus, the likelihood of experiencing a strong Green Paradox, depends on this shape (Jensen, Mohlin, Pittel, & Sterner, 2015). Basically, the underlying question is the following: Is cumulative emission the only relevant determinant of climate change or does a faster, immediate increase in emissions lead to welfare losses which exacerbate damages in the long run?

IV.2. The Shape of the Damage Function and its Importance for the Green Paradox

A linear damage function corresponds to the case that CO_2 emission has a constant marginal damage irrespective of the existing CO_2 stock in the atmosphere and time of emission (Allen et al., 2009; Czupryna, Franzke, Hokamp, & Scheffran, 2020). A convexly increasing damage function features tipping points and implies that certain thresholds of pollution should not be reached (van der Ploeg, 2013; van der Ploeg & Withagen, 2012). In both cases, the cumulative emission is the decisive variable for the level of climate damage.

Conversely, a concavely shaped damage function is driven by the timing rather than the overall amount of pollution. In the net present value calculation, the

[9] There is a vast amount of IAMs, each of which with its own assumptions and analysis goals. The most relevant are probably the DICE (Dynamic Integrated Climate-Economy) model and its variant, the RICE (Regional Integrated Climate-Economy) model – both developed by Nobel Laureate William Nordhaus (see e.g. Nordhaus & Yang, 1996; Nordhaus, 2018). Further popular examples are the FUND (Climate Framework for Uncertainty, Negotiation and Distribution (Tol, 1997)) and the PAGE (Policy Analysis of the Greenhouse Effect (Hope, Anderson, and Wenman, 1993)) models.

climate damage caused by a marginal unit of CO_2 is translated into monetary units and discounted with respect to the time of emission. Hence, if the marginal damage of emission increases at a slower pace than the discount rate, the present value of marginal damages decreases over time (Gerlagh, 2011; Österle, 2016). The argumentation behind a concave damage function reflects the assumption of the Green Paradox theory (Sinn, 2008a, 2012) that postponing extraction is beneficial for social welfare.

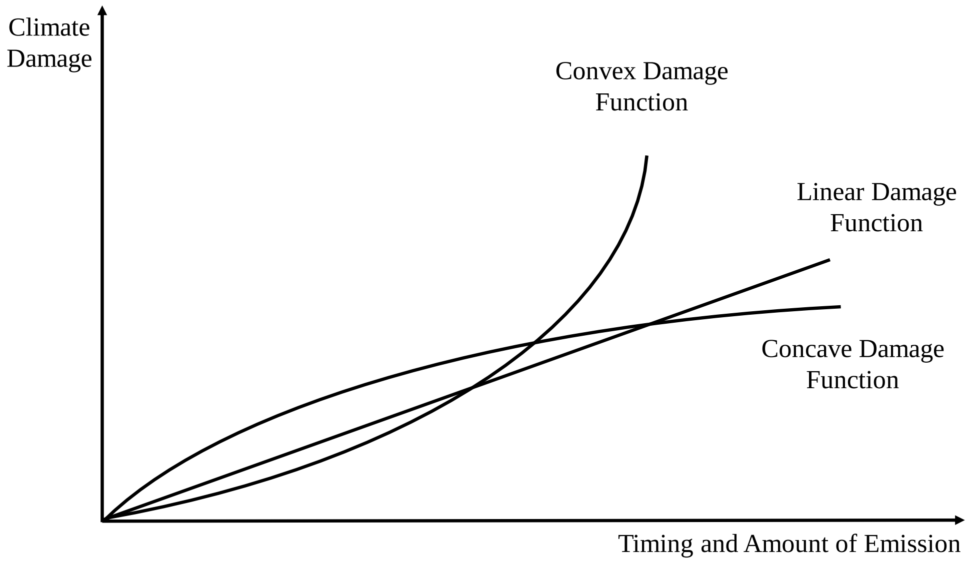

Figure 7: The Potential Shapes of the Damage Function[10]

Source: Own figure

The occurrence of a weak Green Paradox does not depend on the shape of the damage function since the sole determinant is the amount of short-term pollution. Whether a strong Green Paradox arises (i.e. the introduction of climate policies aggravates rather than mitigates climate damages over time) depends significantly on this shape, however. The assumption of a concave damage function makes short-term emission the primary driver of a strong Green Paradox while linear and convex damage functions both render cumulative emission levels more determinant.

The question whether a weak Green Paradox, once occurred, may lead to a strong Green Paradox as well is far from trivial. As mentioned, the answer depends on the shape of the damage function and partwise on the discount rate. In order to

[10] Note that these are idealized visualizations of potential shapes of the damage function that are relevant for the further discussion of the topic. In reality, the damage function is neither perfectly convex, linear nor concave. It may include local variations instead, but the general shape could be defined as one of the three options.

examine this relation in more detail, it is distinguished between two cases: In the former, the damage function is assumed to be concave, and therefore the timing of emission is the more important variable. In the latter case, cumulative emission is considered as more significant for the impact of carbon pollution on the climate (linear or convex damage function).

With a concave damage function, the net present value of damages associated with CO_2 emissions decreases over time because the marginal damage of carbon pollution is presumed to increase at a slower pace than the discount rate (Österle, 2016). Under these circumstances, the implications drawn from the Green Paradox theory, namely that an increase in short-term emission rates should be averted and environmental policies must be designed accordingly (Sinn, 2008a, 2012), are valid. Another implication is that deferring (rather than abating) emission is also beneficial because future climate damage is considered less detrimental than today´s when measured in net present monetary terms.

In the case of an either linear or convex damage function, the image is much different. The assumption of a linear (convex) damage function implicitly sets the discount rate equal to (lower than) the growth rate of marginal climate damages. Hence, simply postponing emissions to a later moment in time does not diminish the environmental problem and abatement is strictly required in order to reduce climate damages. When this abatement takes place is not decisive as the timing of emission is deemed less relevant in this case (Jensen et al., 2015). Furthermore, if a sufficiently high future abatement rate comes at the cost of contemporary increased pollution such that in total emissions decrease, the effect is still desirable as no strong Green Paradox occurs (van der Ploeg, 2013).[11]

It is apparent that, depending on the shape of the damage function, the ways political interventions should be designed very much deviate from each other. If the damage function is concavely shaped, Sinn´s (2008a, 2012) hypothesis that environmental policies are flawed because short-term emissions are enhanced turns out to be well-founded. If, however, the damage function has a shape other than concave, the criticism appears illegitimate.

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[11] In general, the occurrence of a weak Green Paradox is no reason for concern as long as it does not lead to a strong Green Paradox. Even under a concave damage function, a strong Green Paradox could be circumvented if total abatement is sufficiently high to countervail the short-term increase in emissions. Yet, this is much more difficult as short-term emissions are considered to be more relevant for climate damages as cumulative quantities.

Thus, knowing the shape of the damage function is key for successful climate policies. Nonetheless, it is unknown how CO_2 exactly harms the climate and the economy. As aforementioned, climate economists disagree over the shape of the damage function. This is because the climate-scientific community also suffers from uncertainty and continuously reevaluates how the carbon cycle exactly behaves and intertemporally affects the climate (Ballav, Naja, Patra, Machida, & Mukai, 2020; Cox, 2019; Jones & Friedlingstein, 2020). As a result, the damage functions used in IAMs are often outdated and require regular updating in order to estimate the SCC reliably (Bachmann, 2020; Nordhaus, 2018). In fact, the SCC estimates vary and even the most sophisticated IAMs have deviations in their outputs (Hare, Brecha, & Schaeffer, 2018). Thus, it remains essential to find a way to reliably predict the damage function and the corresponding SCC (van der Meijden, van der Ploeg, & Withagen, 2017).

The majority of climate economists deems a linear or convex damage function as more realistic and, hence, short-term extraction secondary to cumulative quantities considering their impact on climate damages (Allen et al., 2009; Czupryna et al., 2020; Jensen et al., 2015; van der Ploeg, 2013; van der Ploeg & Withagen, 2012). Therefore, the dreadful implications of the Green Paradox (Sinn, 2008a, 2012) can be softened. Policies which are curbing fossil stock depletion in the long run are likely to be beneficial – albeit fossil fuel producers may increase supply in the short run (i.e. a weak Green Paradox but no strong Green Paradox arises). Yet, the option of a concave shape cannot be falsified (Jensen et al., 2015) which is why it is important to emphasize that any political conclusion relies on uncertainty about the real shape of the damage function.

V. Demand-Side Solutions

The main criticism that can be withdrawn from the Green Paradox theory (Sinn, 2008a, 2012) is that environmental politics is mainly aiming at the demand side. Corresponding policies are taxes making carbon-intensive energy sources more expensive, quantity constraints limiting the salable amount of these fuels and subsidies enabling zero-emission energy sources to operate competitively to fossil sources. It has been discussed beforehand that Sinn (2008a, 2012) doubts their effectiveness due to countervailing supply reactions. In chapter III., however, it is shown that the expected short-term increase in emission is not certain because endogenous economic factors (endogenous fossil stocks and stock-dependent extraction costs) may decrease future and contemporary carbon pollution rates instead. It is further unclear whether short-term emissions are harmful at all as long as cumulative emission rates can be curbed. In this chapter, the common environmental policies are therefore analyzed in light of the mentioned endogenous factors as well as an undetermined shape of the damage function and it is discussed whether they are indeed flawed.

V.1. Optimal Carbon Tax as First-best Solution

The most discussed form of political intervention in the (fossil) energy market is a carbon tax. Ideally set equal to the estimated SCC, it internalizes the negative externality of fossil fuel combustion. Thereby, it makes consumers and suppliers take the full societal costs of fossil fuel usage into account. By setting the price (US Dollar per metric ton of CO_2) equal to the SCC, emitters face the full rather than only the private costs of their action and optimize their abatement strategy accordingly. For an efficient tax level, the government requires full information on both the SCC (and therefore the social benefit of abating) and the abatement costs of private emitters. This taxation principle is called Pigouvian tax (Pigou, 1920) and guarantees that, apart from ecological improvement, the abatement is also economically efficient – that is marginal cost of abatement equals marginal (social) benefit (Metcalf & Weisbach, 2009).

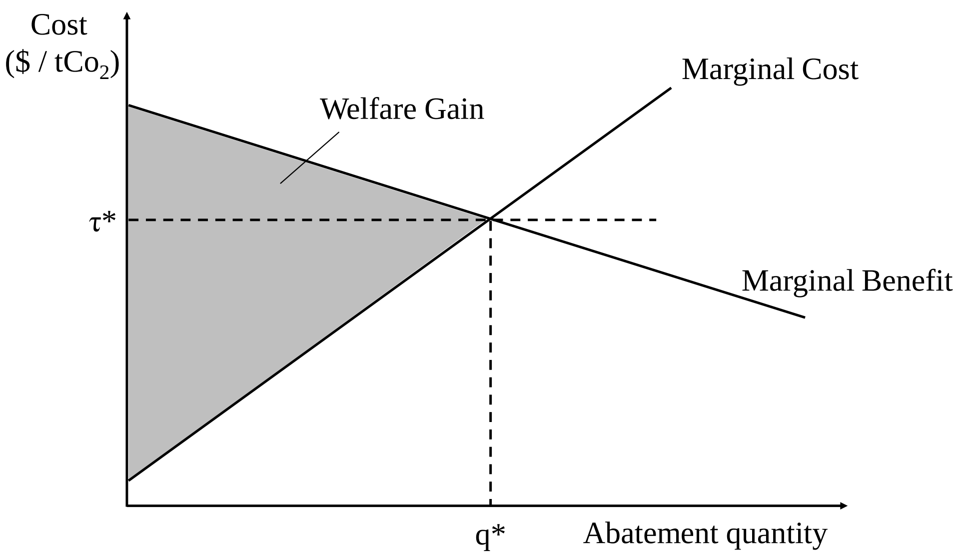

Figure 8: Welfare Gain under a Pigouvian Tax

Source: Own figure based on Metcalf & Weisbach (2009)

Figure 8 illustrates an efficient tax level τ^* and the corresponding abatement quantity q^* under the assumption of linearly increasing marginal costs and a linearly decreasing marginal benefit of abatement. As long as the marginal cost of abating is lower than the tax level, emitters prefer abating over emitting and paying the tax. By setting the tax equal to the intersection of marginal benefit and marginal cost, it is ensured that the efficient quantity of abatement q^* is reached. The societal welfare gain, indicated by the shaded area between marginal cost and marginal benefit curve, arises since the marginal benefit of abatement is higher than the marginal cost given that q^* is not surpassed.

The argumentation in favor of a carbon tax is straight forward. Yet, the issues emphasized by Sinn (2008a, 2012), specifically that supply reactions may be counterproductive and that the implementation of a global carbon tax is not feasible, remain. An optimal tax policy that would solve all issues mentioned is referred to as first-best carbon tax.

The term “first-best carbon tax” is not clearly defined, but there are certain characteristics which can be attributed to it. The tax level should be sufficiently high as of immediately (i.e. without any implementation lag) in order to prevent the distortion effect and, thus, the occurrence of a weak Green Paradox (Hoel, 2012). A tax rate that is high in the beginning and even falling over time would reverse the distortion effect in favor of postponed extraction (Sinclair, 1992). A first-best carbon tax could also be described with a growth rate which is below the interest rate, arguing that this constellation is sufficient in reversing the intertemporal price wedge and, thus, the distortion effect (van der Ploeg, 2013). In general, the optimal carbon tax must be designed in a way that emissions are reduced, both in the short and long run (van der Ploeg, 2015). Furthermore, the tax needs to be implemented on a global scale circumventing free-riding and Spatial Carbon Leakage. By coupling the tax with lump-sum transfers, industry nations can incentivize developing countries to adopt those measures, too (Nordhaus, 2010; van der Meijden et al., 2017). A tax design, that does not trigger an increase in emissions, neither in the short nor in the long run, and is enforced on a global scale, would be an ideal part of environmental politics. With such a measure at disposal, the timing of the transition to the carbon-free era as well as the amount of cumulative carbon emissions could be set in accordance to peak global warming limits (UNFCCC, 2020b; van der Ploeg & Rezai, 2018).

Since an optimal carbon tax reduces cumulative emissions without incentivizing premature extraction, there is no reason for concern about its benefit. The shape of the damage function is not of relevance in this case because there is no trade-off between short and long run emissions. Economic factors like endogenous fossil stocks and stock-dependent extraction costs further enhance the steering effect of the tax and lead to an earlier phase-out of fossil fuels.

A first-best carbon tax may be the ideal theoretical solution for climate change mitigation but remains as such. As Lipsey & Lancaster (1956) conclude, every first-best solution is based on strong assumptions which are often not fulfillable in reality. Sinn (2008a, 2012) also acknowledges the existence of an optimally designed carbon tax in theory. Yet, he underscores that the two main criteria of a first-best solution, namely a high tax level implemented without any announcement delay and the global coverage of that tax, are both not achievable in reality.

According to Sinn (2008a, 2012), the ideal carbon tax policy is one that is very strong initially and pales over time (see also Hoel, 2012; Sinclair, 1992). This sort of policy, however, cannot be assumed to be implementable in a democratic political system due to voter pressure. Economic agents do not act fully rationally and generally suffer under loss aversion. The Prospect Theory (Kahneman & Tversky, 1979) explains this irrationality and implies that economic decisions are not of a pure normative nature. Taking the Prospect Theory into account, the loss aversion of individuals leads to a reduced acceptance of expensive abatement strategies today (Knobloch, Huijbregts, & Mercure, 2019; McLaughlin, Elamer, Glen, AlHares, & Gaber, 2019). The Public Choice Theory (Tullock, 2008) further suggests that public agents also act self-interested and, thus, politicians are not always seeking for the economically superior proposal but tend to follow personal incentives (e.g. getting re-elected).[12] Both theories support the hypothesis that a high carbon tax implemented without an announcement lag is infeasible (Edenhofer & Kalkuhl, 2011; Sinn, 2008a, 2012).

The second requirement of global coverage is also crucial for the tax to be first-best. As discussed in Chapter II.1., a unilaterally implemented policy leads to a distortion on the global fossil market that ultimately results in Spatial Carbon Leakage rendering the policy ineffective if globally measured (Eichner & Pethig,

[12] It is debatable whether a politician acts self-interested if he tries to get re-elected because getting re-elected implies that a majority of voters agrees on the decisions made which is basically the core essence of democracy.

2011; van Long, 2015). Complete international collaboration is required for a carbon tax to be globally enforceable and may be the major obstacle for international environmental politics (Nordhaus, 2019). As countries do not benefit directly from their own efforts in climate change mitigation (Sunstein, 2006), no country has an individual economic incentive to cut its emissions sharply. Even if there is an international environmental agreement (IEA), nations have an incentive not to participate or to overstate their engagement and simultaneously enjoy the spill-over effects from cooperative members. The result is a non-cooperative free-riding equilibrium where few countries put strong efforts in climate change mitigation and the remaining nations enjoy their competitive advantage (Nordhaus, 2019).

IEAs can be very successful, nonetheless, as can be seen with the Montreal Protocol (UNEP, 2020) which prohibited the production and use of ozone-depleting substances like chlorofluorocarbons (CFCs). While the Montreal Protocol (UNEP, 2020) is to date the only UN treaty that has ever been ratified by all 197 UN member states, the Kyoto Protocol (UNFCCC, 2020a) and its successors are severely limited in their global adoption. So why was the Montreal Protocol such a success for global climate cooperation while the global fight against carbon emissions is one of its darkest chapters? Part of the answer lies in the self-interested judgements of the member states. The United States, and many other countries alike, have a positive cost-benefit relation for the abatement of CFCs and, therefore, a strong incentive to cooperate in the Montreal Protocol (Sunstein, 2006). For climate agreements on CO_2 emissions, the opposite image occurs: The benefit generated from their personal efforts is less than the related costs (Barrett, 1994; Sunstein, 2006) which led the United States to withdraw from the Paris Agreement (UNFCCC, 2020b). If countries have an economic incentive to leave an IEA, there is a strong need for international institutions that can enforce participation and commitment. So-called self-enforcing international environmental agreements (Barrett, 1994) must make it attractive for countries not to leave – this implies that following the unilateral benefit of leaving must be penalized in such a way that leaving is rendered unattractive. This sanction has to be credible in order to disincentivize nonparticipation and must be enforced by a supranational institution (Barrett, 1994). Since it is not credible that the countries which are committed to climate change mitigation go into a trade or armed war with the nonparticipating nations in order to enforce the Paris Agreement, there is little incentive to stay in this IEA

(Nordhaus, 2019). Therefore, in the absence of a self-enforcing international environmental agreement on carbon emissions, global coverage is infeasible and a first-best carbon tax unattainable.

Apart from the issue of global coverage, the literature disagrees on whether a single carbon tax is indeed the first-best policy option to curb carbon emissions. Some scholars doubt that a tax alone can introduce an incentive strong enough to reach the Paris climate goals (UNFCCC, 2020b) and suggest supplementary policies like subsidies on renewable energy sources (e.g. High-Level Commission on Carbon Prices, 2017; Rezai & van der Ploeg, 2017). Others even depart from the recommendation of a single carbon price across industry sectors and national borders. Stiglitz (2019) pleads for high taxes in carbon-intensive sectors such that low-emission parts of the economy can be relieved. In general, he claims that carbon taxes should be set equal to the shadow prices of carbon (i.e. the SCC) which vary across time, over space, and with different uses. In order to circumvent distributional conflicts, a single global carbon tax is therefore not desirable (Stiglitz, 2019).

Nonetheless, despite disagreeing on its required design, the scientific community is convinced that a carbon tax, even with some necessary amendments, is an essential part of climate change mitigation strategies (High-Level Commission on Carbon Prices, 2017).

V.2. Second-best Carbon Tax

In economic optimization problems, the attainment of the first-best solution requires the simultaneous fulfillment of all optimum conditions. As soon as one of these conditions is not fulfilled – in case of the carbon tax, this is given by the required global coverage and nonexistence of an implementation lag – the first-best solution is unattainable. The succeeding optimization is subject to constraints and, thus, results in a second-best optimum. It is hardly possible to design a single second-best solution because full information on the departure from the optimum conditions would be required in order to set up a unique second-best optimization. Hence, the General Theory of Second Best (Lipsey & Lancaster, 1956) states that, depending on the assumptions about the constraints, different second-best outcomes occur. Concerning Sinn´s (2008a, 2012) assumption that a carbon tax can be implemented neither globally nor at a sufficiently high level without an implementation lag, characteristics of a second-best carbon tax are discussed in the following and it is shown how they correlate with the theory of a weak and strong Green Paradox.

The first presumption that a global carbon tax is not feasible is commonly shared. Hence, unilateral mitigation strategies must be considered and designed such that the magnitude of Spatial Carbon Leakage is hold at a minimum. Besides the already discussed leakage of primary energy sources (see chapter II.1.), there is another leakage channel through the international trade of consumption goods. Therefore, the aim should be to prevent the outsourcing of carbon-intensive production to non- (or less) taxing countries. On this behalf, a consumption-based carbon tax implemented by full border carbon adjustment may be an adequate alternative to the so far proposed global, production-based carbon tax (Eichner & Pethig, 2015).

The second constraint a second-best carbon tax is facing, is the necessity for implementation lags and gradually rising tax levels due to public acceptance pressure. Major regulatory efforts will always come with an implementation lag that incentivizes suppliers to bring forward extraction (Di Maria, Lange, & van der Werf, 2014; Smulders et al., 2012). However, endogenous stock capacities and the interrelated divestment effect (see chapter III.1.) counteract the distortion effect and may be able to prevail (Bauer et al., 2018). A gradually rising carbon tax is also not necessarily a reason for concern. As explained in chapter II.2., a falling tax rate induces postponed extraction and, hence, is favorable. Nevertheless, a falling tax rate on greenhouse gas emissions is neither easy to publicly explain nor a policy governments can reliably commit to. Yet, it is not required for the tax rate to decrease in absolute terms. If it increases less rapidly than the rate of interest, the discounted price wedge decreases over time and the desired effect is still reached (Edenhofer & Kalkuhl, 2011). With the discounted price wedge decreasing over time, the distortion effect reverses such that fossil fuel suppliers prefer deferred extraction rather than bringing it forward.

Figure 9 visualizes the effect a discounted price wedge has on the intertemporal distribution of extraction. If the tax rate rises at a slower speed than the interest rate does, the discounted price wedge in the second period is smaller than the corresponding one in the first period (τ_1 x P_1 > $\frac{\tau_2\, x\, P_2}{1+i}$) which results in deferred extraction ($R_2 > R_1$).

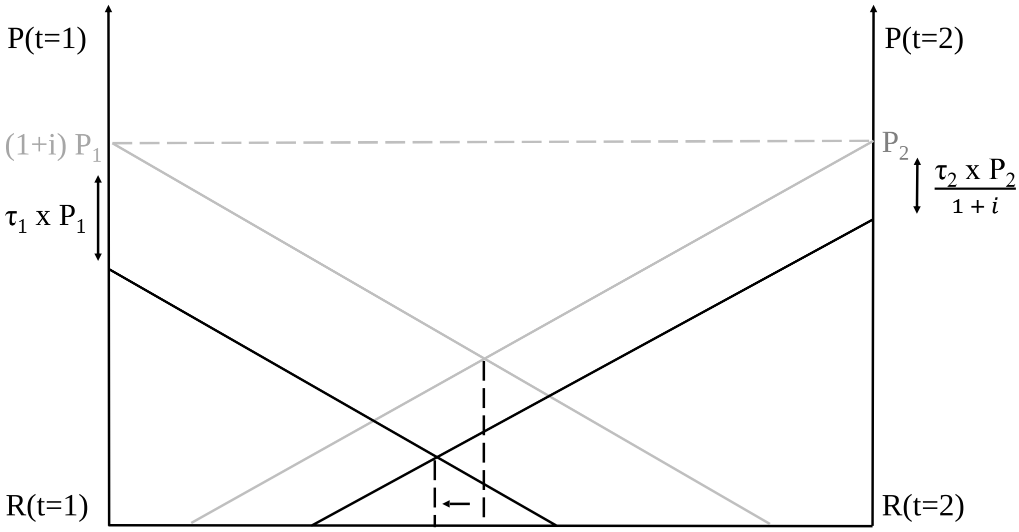

Figure 9: Reversed Price Wedge

Source: Own figure

A carbon tax designed as described is able to reduce short-term emissions and, in combination with stock-dependent extraction costs, also the cumulative amount of economically recoverable fossils. Therefore, a tax with a growth path less steep than the interest rate could be assumed as first-best (van der Ploeg, 2013).

Thus, a carbon tax, that is unilaterally implemented, comes with an announcement lag and is gradually rising over time, may still be a valid policy of climate change mitigation. Obviously, the lack of global commitment towards common carbon pricing brings along certain difficulties in form of Spatial Carbon Leakage. Furthermore, due to country-specific fiscal heterogeneity, international differences in fossil fuel taxation will most probably remain high in the future (D'Autume, Schubert, & Withagen, 2016; Najm, 2019) and may only partwise be subject to cross-border adjustments. Nevertheless, the dooming assessment of the Green Paradox theory (Sinn, 2008a, 2012) about demand-side tax policies can be softened. It is neither certain whether an increase in short-term emissions is indeed harmful for the earth´s climate (no strong Green Paradox depending on the shape of the damage function) nor whether a second-best carbon tax leads to an increase in current emissions at all (no weak Green Paradox either).

V.3. Second-best Renewable Subsidy

Although carbon pricing is considered as an essential part of any climate change mitigation strategy, it may not be sufficient to induce modifications at the pace and to the extend required for the Paris target to be met (High-Level Commission on Carbon Prices, 2017). Therefore, it needs to be supplemented with other measures tackling further market failures. The two main externalities on the energy market are emissions through combustion and learning-by-doing spillover effects. The negative externality imposed on society by carbon pollution can be internalized by carbon taxation. The positive externality of learning-by-doing is a blessing for society rather than a burden and, thus, needs to be reimbursed (Arrow, 1962; Edenhofer et al., 2005). The common tool to internalize the latter one is a subsidy on renewable energy generation. This subsidy can come in different forms, for instance as research and development funding or as a higher feed-in tariff, but the general incentive is the same: The cost competitiveness of renewables acting as clean backstop technology is enhanced. Thereby, the price ceiling of fossil fuels is successively lowered and their extraction is eventually rendered uneconomical (Rezai & van der Ploeg, 2017). The literature predominantly agrees that such a subsidy is a necessary complement for any carbon tax and gains further importance as a first-best tax design is unattainable (High-Level Commission on Carbon Prices, 2017; Rezai & van der Ploeg, 2017; Storrøsten, 2020).

In his argumentation about the Green Paradox theory, Sinn (2008a, 2012) doubts that a price-driven substitution of fossil fuels will take place in the foreseeable future. Thus, he implicitly questions the effectiveness of subsidies on renewable energy sources.

Unlike Sinn (2008a, 2012), many scholars consider the phase-out of fossil fuels both plausible and essential – with subsidies acting as a key policy besides carbon pricing (e.g. Acemoglu, Aghion, Bursztyn, & Hemous, 2012; Baldwin et al., 2020; Grafton, Kompas, & van Long, 2012). The optimal level of this subsidy can be derived analogously to the corresponding one of a Pigouvian tax. Under business as usual, the amount of renewable energy generation is suboptimally low because the producers only take their private marginal benefit into account. In order to internalize the positive spillover effect (i.e. the social benefit of renewable energy production is higher than the private), producers need to be financially incentivized.

Figure 10 shows the effect of such an incentive. Without government intervention, the producers set their private marginal benefit (MB) equal to their marginal costs (MC) and generate Q^{bau} at a price level of P^{bau}. As the marginal social benefit (MSB) is higher than the private, a deadweight loss occurs under business-as-usual (DWL^{bau}).

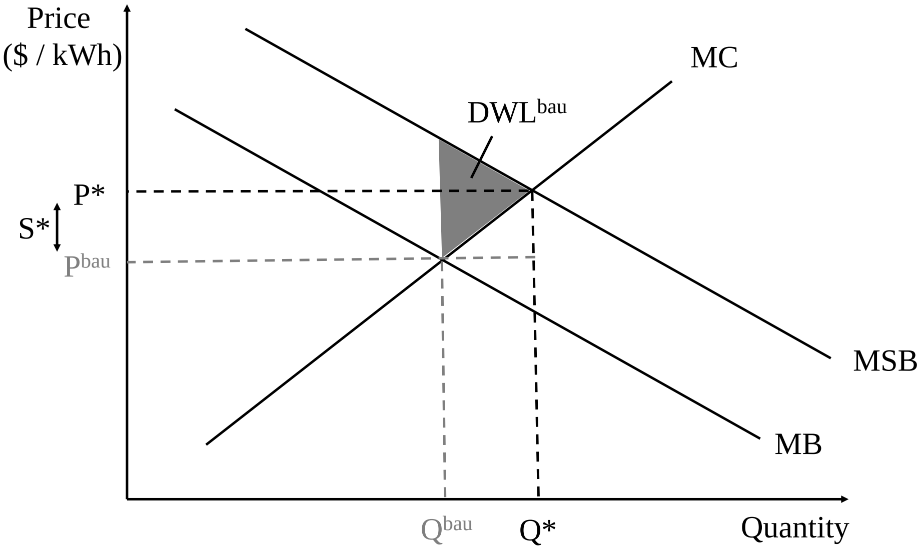

Figure 10: Welfare Gain under a Renewable Subsidy

Source: Own figure

This deficiency can be prevented by granting a subsidy S* on renewable energy production. The new equilibrium price level P* (= P^{bau} + S*) sets the generated energy quantity Q* to equalize marginal costs with the marginal social benefit (MC = MSB). An equilibrium set in accordance to the MSB implies that the learning rate is optimized. Thus, the price decline of the carbon-free technology happens at an efficient pace (Arrow, 1962; Edenhofer et al., 2005). This price decline of renewable energy sources is at the core of climate change mitigation efforts and, in combination with a carbon tax, a leverage to phase-out fossil fuel usage (European Commission, 2020b; Storrøsten, 2020). The policy-driven approach to eventually render fossils more expensive than renewables is further enhanced by endogenous characteristics like rising stock-dependent extraction costs in the fossil fuel market.

Assuming that renewable subsidies are effective, brings back the initial issue of the Green Paradox. If renewable energy will indeed push fossils out of the market and this target date is brought forward by green subsidies, fossil fuel suppliers anticipate this effect and also bring forward extraction as soon as they are faced with a subsidy on renewable energy sources (Gerlagh, 2011; Hoel, 2009). In this case, a weak Green Paradox arises while cumulative emissions are reduced (Rezai & van der Ploeg, 2017).

Once again, the trade-off between short-term and cumulative emissions as well as their associated climate damages determine whether a policy is beneficial or not. It might be assumed that under a non-concave damage function the cumulative effect outweighs the short-term effect and a green subsidy is a valuable policy for mitigating global warming. Yet, this assumption remains under uncertainty. But it is further uncertain whether short-term emissions are indeed increased because anticipative fossil suppliers limit their investments in exploration activities and the corresponding divestment effect countervails the distortion effect (Bauer et al., 2018). As a result, the increase in immediate emissions is reduced and might also vanish depending on the magnitude of the two opposing effects.

Hence, similar to the case of a second-best carbon tax, scholars disagree on whether a weak Green Paradox is triggered by the introduction of a subsidy on renewable energy sources. Even if it is triggered, it is further unproven whether it is decisive for the occurrence of a strong Green Paradox.

It can be concluded that the scenario most supported in the literature includes a weak Green Paradox but no strong Green Paradox and, therefore, endorses the opportunity of demand-side policies.

V.4. Cap-and-Trade System

It has been argued that a carbon tax is indispensable for emission reduction efforts. Yet, there is a different market-based solution: emission trading systems (ETS) with popular examples in California, the European Union and as of 2020 also China (California Air Resources Board, 2020; European Commission, 2020a; IEA, 2020). By setting a cap on the total amount of CO_2 emissions in a given time period and continuously lowering this cap, such an ETS ensures the desired abatement pace. Emitters can trade emission permits with each other which further leads to an efficient abatement allocation (i.e. companies which are able to abate more cheaply will reduce their emissions stronger than those who struggle in doing so).

This brings along the huge advantage that the implementing government does not need full information, neither on the level of SCC nor on the abatement costs of the individual private emitters. Information asymmetry is a major drawback for carbon taxes and may be the foremost reason to prefer an ETS over a carbon tax (Stiglitz, 2019). Another advantage of the cap-and-trade approach is the fixed amount of emissions in each period of time. Therefore, even if the cap is falling sharply, there is no weak Green Paradox (in the absence of Spatial Carbon Leakage) because short-term emissions cannot surpass the cap. The necessity for implementation lags may nonetheless induce a smaller weak Green Paradox (Jensen et al., 2015).

The nonexistence of a self-enforcing international environmental agreement (Barrett, 1994) imposes the same obstacles to a coherent global ETS as it is the case for an analogous carbon tax. However, connecting existing regional carbon markets based on a cap-and-trade system is more feasible than agreeing on a uniform carbon tax from scratch. Regional ETS initiatives can therefore pave the way for binding IEAs later on (Beccherle & Tirole, 2011; Tirole, 2016).

VI. Source Tax on Capital Income as Supply-Side Solution

In accordance to his criticism about demand-side measures, Sinn´s (1984) main proposal for the environmental-political dilemma is a source tax on capital income. Based on the Hotelling Rule, he argues that the financial assets of fossil fuel suppliers should be made less attractive in order to indirectly appreciate the natural capital in form of fossil reserves. Such a source tax reduces the profit generated by extracting today, investing the revenue on the capital market and earning interest. Thus, the second option of leaving the commodity in situ and earning a price appreciation through scarcity rents becomes relatively more attractive (Sinn, 1984). Setting the capital income instead of the revenue from fossil sales as tax base, amends the Hotelling equation to the following (Sinn, 2008b):

$$i(1-\tau_i) = \frac{P(R,t)}{g(S)} \tag{5}$$

As the interest profit is reduced by the source tax on capital income τ_i (left side of the equation), the appreciation rate of the fossil stock (right side of the equation) must also shrink in order for the intertemporal extraction decision to find a new equilibrium. This implies that the scarcity-driven price path and, hence, the extraction path would have to flatten. This postponement of extraction is the desirable outcome following Sinn´s (2008a, 2012) argumentation that it is preferable to have the damages occurring sometime in the future rather than today (concave damage function).

Conversely, a carbon tax affects the right side of the equation and, if ill-designed, reduces extraction profitability over time. Therefore, it induces preponed extraction (for a detailed explanation on this price wedge see chapter II.2.).[13]

Like the case of demand-side solutions, the problem with a source tax on capital income as supply-side solution is less theoretical than practical. Capital income taxation is widely existing all over the world and, thus, not a new invention. However, as income taxes are levied in accordance with the residence principle, companies can evade taxation by shifting their legal base to low or non-taxing countries (i.e. tax havens) (Miranda & Dias, 2020). Only if these tax havens are forced to cooperate in international financial disclosure agreements that allow for automatic exchange of information, income taxation becomes a sound policy (Ahrens & Bothner, 2020; Sinn, 2008a, 2012). With the OECD (Organization for Economic Cooperation and Development) Base Erosion and Profit Shifting (BEPS) project (OECD, 2020b), over 135 countries are collaborating to put an end to tax avoidance strategies (Young, 2018). They are thereby paving the way for international tax systems like the proposed source tax on capital income of fossil fuel suppliers. An IEA in form of capital income taxation would yield major fiscal benefits for basically all participating countries. Therefore, unilaterally breaching the contract could be credibly penalized by the other agreement participants. Based on the Inclusive Framework on BEPS (OECD, 2020b), a source tax on the capital income of fossil fuel suppliers would be a self-enforcing IEA (Barrett, 1994) and a plausible climate solution according to Sinn´s (2008a, 2012) argumentation.

Yet, Sinn (2008a, 2012) bases his reasoning on the assumption of a concave damage function. That being assumed, short-term emissions should be curbed and cumulative emission effects are less relevant. As explained in the previous chapters, this is a very critical assumption and reducing cumulative emissions must be a key part of environmental policies as long as it is unproven whether short-term emissions are truly the major determinant of climate damages. Because a capital income tax only mitigates the distortion effect and does not reduce cumulative extraction, it is not capable to achieve low stabilization targets in accordance to the

[13] Note that neither a carbon tax nor a source tax on capital income is to be confused with a corporate tax. Both can be considered as mutually exclusive subcomponents of corporate taxation as the tax base of corporate taxation generally is the overall income. Hence, a corporate tax would affect both sides of the Hotelling equation leaving the extraction decision of fossil fuel suppliers indifferent.

Paris Agreement (Edenhofer & Kalkuhl, 2011; UNFCCC, 2020b). Therefore, its effectiveness in curbing climate damages over the long run is doubtable.

VII. Empirical Discussion

The Green Paradox theory (Sinn, 2008a, 2012) has been widely analyzed in the theoretical literature and partwise refuted. However, the theoretical analysis lacks an adequate empirical foundation. There are isolated empirical studies like the one of Di Maria et al. (2014) on the Acid Rain Program and the corresponding sulfur tax implementation in the United States, the study of Grafton, Kompas, van Long, & To (2014) on the effect of a biofuel subsidy in the United States, Lemoine (2017) on the U.S. cap and trade vote in 2011, Steinkraus (2019) on the effect of deviating implementation lags between U.S. states and Yang, Li, & Tang (2020) who empirically assess the impact of environmental haze pollution regulation in different Chinese regions. Yet, these studies are equivocal in their results.

In the first empirical test of the Green Paradox hypothesis, Di Maria et al. (2014) analyze the five-year implementation lag of a sulfur tax which was announced in 1990 as part of the Acid Rain Program of the United States (EPA, 1990). The announcement indeed triggered a price decrease of coal because suppliers feared that the sulfur taxation will limit their future salability. The authors cannot find clear evidence for a weak Green Paradox, however. Due to market conditions such as long-term contracts and concurrent regulation, only few power plants reacted to the price drop and short-term emissions did not significantly increase.

Grafton et al. (2014) use energy data from the period between 1981 and 2011 to observe whether U.S. biofuel subsidies provided an incentive for fossil fuel producers to bring extraction forward. Opposing the result of Di Maria et al. (2014), they find significant evidence for a weak Green Paradox. Their data further suggests that the legislation is likely to have resulted in a strong Green Paradox as well.

Lemoine (2017) also reports evidence of a Green Paradox that has been caused by a proposed emissions trading system in the United States. In 2009, the U.S. House of Representatives passed a bill to cap CO_2 emissions as of 2013. Until the U.S. Senate voted on the bill in 2010, the study´s data discloses strongly increased emissions. Since the Senate turned down the legislation, the short-term increase in emissions is not balanced by a cumulative effect. Hence, a weak and a strong Green Paradox have been caused.

These clear evidences in favor of the Green Paradox theory are countered by Steinkraus (2019) who analyzes four major coal-producing U.S. states that announced a greenhouse gas action plan during the 2000s. While one of the states experienced a high and statistically significant increase in coal production, there is no evidence for a weak Green Paradox in the other three.

A more recent empirical study is about haze pollution in China. Yang et al. (2020) compare the relationship between regional environmental regulations and haze pollution in 30 Chinese provinces between 2004 and 2016 and develop results supporting the existence of a Green Paradox.

The empirical literature slightly points towards the existence of a weak Green Paradox but indicates that, unless the legislation shattered, a strong Green Paradox can be prevented, nonetheless. Notwithstanding, further empirical analysis on the impact of environmental legislation on short- and long-term emission quantities is required in order to assess the broad theoretical literature. Study panels that allow for a comparison between legislating and non-legislating regions, preferably within the same country and, thus, similar economic circumstances, provide a suitable background for further empirical studies. These characteristics are best found in countries with a federal state system (e.g. the United States) where neighboring states can have deviating environmental legislations.

After all, it has to be mentioned that the equivocal study results should not be seen as contradictions. The occurrences of a weak and a strong Green Paradox strongly depend on the energy-economic structures of the market that is being analyzed. Thus, it would come as no surprise if future empirical observations might also disclose both, evidence for the existence and the non-existence of a Green Paradox. If this prediction turns out to be true, future research should aim for linking the occurrence of a Green Paradox to specific market conditions. Vice versa, it should also be analyzed which characteristics prevented it in case that no significant evidence was found.[14]

[14] The study of Di Maria et al. (2014) comprehensively shows how data about the Green Paradox can be linked to prevalent market conditions and is a sound example for future research on this matter.

VIII. Conclusion

Hans-Werner Sinn (2008a, 2012) has argued in his theory about the Green Paradox that the supply side is not being paid enough attention to when climate legislation is made. The result are pure demand-side policies that are flawed and suffer from little effectiveness. This is because a carbon tax aiming at curbing carbon-intensive energy consumption comes with an implementation lag and rises over time. Both are incentives for fossil fuel suppliers to bring extraction forward and, hence, exacerbate short-term emission. A subsidy on renewable energy generation has a similar effect and also triggers the distortion effect according to Sinn (2008a, 2012).

However, it is explained in this thesis that there are economic factors that oppose the occurrence of a Green Paradox. Less revenue from future fossil sales limits the profitability of investments in exploration and research activity and, thus, reduces the endogenous fossil stock. Stock-dependent extraction costs further contract the profit from fossil fuel extraction. In combination with a renewable backstop technology, the price-based substitution of fossil fuels is thereby made feasible. Another opposing factor is the risk of owning stranded assets within fossil fuel dependent value chains which affects supply and demand. By anticipating the phase-out of fossil fuels, power utilities and corporations are prematurely shifting their energy demand to carbon-free sources. Hence, they proactively limit the scope for fossil suppliers to expand sales in the short run. These endogenous factors are mitigating the weak Green Paradox and, depending on the specific market characteristics, may be able to prevent its occurrence.

Even if a weak Green Paradox does occur, this is not necessarily a reason for concern. The shape of the damage function plays a key role for the effect of emissions on climate damages. A concavely shaped function is supporting Sinn´s (2008a, 2012) view that short-term emissions must be curbed. A linear or convex damage function, however, yields cumulative emission quantities to be the driving force of climate change. Therefore, it is not an issue if short-term emissions increase as long as cumulative quantities can be significantly constrained.

The latter assumption endorses the implementation of demand-side solutions such as carbon taxes, emission trading systems and subsidies on renewable energy generation. Even though a first-best carbon tax is infeasible due to the non-existence of a self-enforcing international environmental agreement and the necessity of implementation lags, second-best solutions can still be sound policy measures. A second-best carbon tax that is rising at a slower pace than the interest rate reverses the price wedge and induces both a postponement of extraction and less overall supply quantities. A cap and trade system limits the possibility for a weak Green Paradox as well because the emissions in each period of time are capped. By setting a sufficiently restrictive initial cap, the short-term emissions can thus be controlled.

The issues of Spatial Carbon Leakage and the implementation lag remain nonetheless under any second-best solution. Yet, connecting existing carbon markets under regional emission trading systems may be an option towards a global solution and, hence, a remedy for Spatial Carbon Leakage. When implementing these cap-and-trade systems, governments do not require full information on the social cost of carbon and private abatement costs. These may be the major reasons why the contemporary international efforts on carbon abatement are primarily based on emission trading systems.

Sinn´s (2008a, 2012) own proposal for the climate legislation dilemma, namely a source tax on the capital income of fossil fuel owners, is insensitive to design flaws as such a tax always incentivizes fossil fuel suppliers to postpone extraction. However, the existence of tax havens reduces its effectiveness. Even if they were shut down, a source tax does not yield any cumulative effect as it does not render extraction itself unprofitable.

The whole discussion about the Green Paradox is based on uncertainty about the shape of the damage function. It is therefore unclear whether short-term emissions or cumulative CO_2 quantities are more determinant for the incidence of a strong Green Paradox. The scientific community slightly favors the view that a concave damage function is not realistic and, thus, that the main goal of environmental policies should be to suppress cumulative carbon emissions. Albeit this assumption is not proven, it softens the dramatic conclusion of Sinn (2008a, 2012) that demand-side policies are aggravating climate change.

In general, reliable data on the relation of amount and timing of emission to climate damages is pivotal in order to assess which sort of environmental policies will be the most beneficial. Furthermore, a broader empirical founding of the Green Paradox debate is required as it is still equivocal whether existing demand-side measures are indeed triggering a weak Green Paradox. Without this data basis, governments can hardly credibly commit to any long-term strategy – although the economy needs political stability in order to design the energy transformation efficiently.

In conclusion, Sinn (2008a, 2012) is right about his criticism that the supply side is not sufficiently considered and deserves credit for launching the Green Paradox debate. His proposal of a source tax on capital income as well as his argumentation that demand-side measures are ineffective in mitigating climate change must be regarded with caution, however. A concave damage function and, therefore, the presumption that short-term emissions are the key force towards a strong Green Paradox are likely to not reflect reality.

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